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(54) **Process for fabricating tapered microstructured fiber system and resultant system**

Verfahren zum Herstellen von verjüngtem mikrostrukturiertem Fasersystem und resultierendes System

Procédé de fabrication d' un système a fibre conique microstructurée et système en résultant

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Description

BACKGROUND OF THE INVENTION

Field of the Invention

[0001] The invention relates to optical communications systems using microstructured optical fiber.

Discussion of the Related Art

[0002] Microstructured optical fiber, e.g., fibers containing capillary air holes, are known. Such fibers have experienced renewed interest due to a variety of interesting properties observed, including supercontinuum generation and soliton generation. See, e.g., B.J. Eggleton et al., "Cladding-Mode-Resonances in Air-Silica Microstructure Optical Fibers," Journal of Lightwave Technology, Vol. 18, No. 8 (2000); J.C. Knight et al., "Anomalous Dispersion in Photonic Crystal Fiber," IEEE Photonics Technology Letters, Vol. 12, No. 7 (2000); J. Ranka et al., "Visible continuum generation in air-silica microstructure optical fibers with anomalous dispersion at 800 nm," Optics Letters, Vol. 25, No. 1 (2000); and U. S. Patents Nos. 5,907,652 and 6,097,870. While these fibers have generated interesting and attractive properties, several practical difficulties exist. For example, many of these unique properties are found in microstructured fiber that have an extremely small core. Coupling light efficiently into such a fiber is thus a significant hurdle. In addition, the robustness of such fibers is sometimes in question. A variety of similar hurdles stand between the current state of the art and commercial feasibility.

[0003] Thus, improvements in fabrication and design of systems utilizing microstructured optical fiber, as well a new ways to develop and manipulate the fiber itself, are desired.

[0004] WO-A-00 49 435 discloses a photonic crystal fibre including a plurality of longitudinal holes, in which at least some of the holes have a different cross-sectional area in a first region of the fibre, that region having been heat-treated.

Summary of the Invention

[0005] A process and a system according to the invention are as set out in the independent claims. Preferred forms are set out in the dependent claims.

[0006] The invention relates to improved techniques for utilizing microstructured optical fibers in a variety of systems, e.g., techniques for manipulating microstructured fiber, forming robust small-diameter microstructured fiber, and/or for manipulating modes propagating through a microstructured fiber. The process is relatively straightforward and also provides for efficient incorporation and operation of the resultant fiber in a communications system.

[0007] Stated generally, the invention involves providing a microstructured fiber having a core region, a cladding region, and one or more axially oriented elements (e.g., capillary air holes) in the cladding region. A portion of the microstructured fiber is then treated, e.g., by heating and stretching the fiber, such that at least one feature of the fiber microstructure is modified along the propagation direction, e.g., the outer diameter of the fiber gets smaller, the cross-section of the axially oriented elements get smaller, or the axially oriented elements collapse. The treatment is selected to provide a resultant fiber length that exhibits particular properties such as mode contraction (optionally leading to soliton generation) or mode expansion. Advantageously, the process is performed such that the resultant fiber length is able to readily be coupled to a standard transmission fiber, i. e., the core sizes are similar, which allows efficient coupling of light. (Modified along the propagation direction indicates that as one moves along the propagation direction, one or more aspects of the microstructure vary. Outer diameter indicates the diameter of the outermost cladding, not including any protective coating. Fiber length, as used herein, indicates the entire structure, i. e., untreated and treated fiber sections.) Fiber lengths fabricated according to the invention are useful for a variety of applications, including dispersion management, optical regeneration, reshaping, and retiming, providing nonlinear effects such as soliton generation, soliton self-frequency shift, and pulse compression, and providing efficient coupling into laser diodes and similar devices.

[0008] In one embodiment, reflected in Figs. 1A and 1B, the treated portion of the fiber 10 is heated and stretched to form at least one tapered region 22, 23 and a waist region 24, the tapered region(s) leading from an untreated portion of the fiber to the waist region. Typically, the microstructure of the fiber is maintained in the at least one tapered region, and in at least a portion of the waist region. In fact, one way to readily fabricate sections of small-core microstructured fiber of the type discussed above is to stretch a larger profile microstructured fiber. And, moreover, because a portion of the fiber retains its original core diameter, light from an adjacent transmission fiber is capable of being efficiently coupled into the microstructured fiber length. The resultant structure is, for example, capable of highly advantageous soliton self-frequency shift, discussed in more detail below. (Maintenance of the microstructure in the tapered region and/or the waist region, as used herein, indicates that the presence and arrangement of at least a portion of the axially oriented elements are maintained, although likely in a different size and proportion than in the initial fiber; it is possible that a doped core present in the initial fiber will essentially disappear in the waist region, but such an effect does not indicate that the microstructure has not been maintained.)

[0009] Significantly, the above embodiment is typically performed such that light propagating through the waist region fiber is confined by the axially oriented el-

ements, e.g., by the capillary air holes. Confined, as used herein, indicates confinement due to the effective refractive index profile provided by the combination of the silica and the axially oriented elements, or due to a bandgap effect provided by periodically disposed axially oriented elements. In this respect, the invention constitutes a significant improvement over prior art systems that used tapering techniques. For example, in T. A. Birks et al., "Generation of an ultra-broad supercontinuum in tapered fibres," CLEO'00, postdeadline paper CPD30 (2000), the authors report tapering a conventional optical fiber, i.e., a non-microstructured fiber, down to a waist region having a diameter less than 2 μm. At this small diameter, the core essentially disappears, and the entire fiber diameter then constitutes a core region with the cladding provided by the surrounding air. While unique properties of the type discussed above were exhibited by the stretched fiber, the fact that the surrounding air provides the cladding renders the design commercially unfeasible. Specifically, not only does the waist region becomes highly sensitive to bending - i.e., bends introduce loss, but a polymer re-coat of the waist region modifies the air-silica boundary and thereby similarly introduces loss. Thus, the system described by Birks et al. is not robust enough for feasible commercial use.

[0010] In contrast, according to the above embodiment of the invention, the axially oriented elements present in the waist region fiber confine propagating light therein, i.e., provide an effective cladding. Because the outside of the fiber is therefore not functioning as the cladding, the resultant waist region is highly robust. Specifically, since the exterior air is not used as cladding, a larger diameter can be provided, i.e., there can be additional silica surrounding the axially oriented elements, which improves the robustness of the waist region. Moreover, also in contrast to the Birks et al. fiber, the fiber of the invention is able to endure bending as well as a polymer re-coat, further increasing the ease with which the overall fiber length is able to be incorporated into a system.

[0011] In another embodiment of the invention, reflected in Fig. 2, the microstructure of the initial fiber is treated such that axially oriented elements (typically capillary air holes) are partially or fully collapsed in at least part of the treated portion of the fiber, while the overall diameter of the treated section remains about the same as the untreated section (e.g., the diameter of the treated portion is generally at least 90% of its original diameter). (Partial collapse indicates a reduction in cross-section of the elements, but with the elements still intact.) This gradual collapse as one moves along the propagation direction is able to provide mode expansion, i.e., the effective refractive index profile provided by the presence of the axially oriented elements disappears, leaving a silica cladding in its place. Such mode expansion is useful, for example, in a variety of applications were conversion into a larger mode is desired, e.g., to minimize coupling losses between a fiber and another element such as a larger area detector or a laser diode (see, e.g., W.T. Chen and L.A. Wang, "Laser-to-fiber coupling scheme by utilizing a lensed fiber integrated with a long-period grating," IEEE Photonics Tech. Lett., Vol. 12, No. 5, 501-503 (2000)). Such gradual collapse is also possible in combination with some stretching. For example, it is possible to take a microstructured fiber, collapse the air holes at one end, which enhances splicing and coupling to standard transmission fiber, and stretch another portion of the fiber to provide desired properties.

BRIEF DESCRIPTION OF THE DRAWINGS

[0012]

Figs. 1A-1C reflect an embodiment of the invention.
Fig. 2 reflects a further embodiment of the invention.
Figs. 3A and 3B illustrate the characteristics of a fiber length made according to the embodiment reflected in Figs. 1A-1C.
Figs. 4A and 4B illustrate properties of the fiber length represented in Figs. 3A and 3B.
Fig. 5 illustrates further properties of the fiber length represented in Figs. 3A and 3B.

DETAILED DESCRIPTION OF THE INVENTION

[0013] One embodiment of the invention is illustrated in Figs. 1A-1C. A microstructured optical fiber 10 is provided. The fiber 10 comprises a core region (e.g., a germanium-doped core 12), a cladding region 14, and axially oriented elements located in the cladding region - in this embodiment six capillary air holes 16. (It will be apparent that the number of air holes are capable of being widely varied depending on the particular application for the fiber.) For such a fiber having core and outer diameters of a typical communications fiber, e.g., core diameter of about 10 μm and outer diameter of about 125 μm, the capillary air holes 16 will generally play substantially no role in waveguiding - they are sufficiently removed from the central region to substantially avoid influencing the fundamental mode, and will only play a role in the treated region, as discussed below. (In other embodiments, it is possible for the axially oriented elements to contribute to waveguiding in the initial fiber.)

[0014] The microstructured fiber is fabricated by any suitable method. For example. it is possible to form the core and inner cladding by a conventional technique such as MCVD. In such a case, the core glass, optionally doped with a material such as germanium, is deposited on the inside of an inner cladding tube, and the tube is then collapsed into a solid core rod. The preform is then typically completed by providing appropriate structural members on the periphery of the rod, e.g., capillary tubes, which are generally attached by melting or physical bundling, followed by overcladding of the resultant

structure. The assembly is then generally consolidated into a preform, and the preform is ready to be placed into a draw tower, where fiber is drawn according to conventional techniques.

[0015] It is also possible to fabricate the microstructured optical fiber by a sol-gel technique, such as discussed in EP application no: 01300525.1.

[0016] Described generally, this technique involves providing a vessel (typically tube shaped), with elongate elements (e.g., wires, needles, or fibers) extending at least a portion of the length of the vessel and provided in a predetermined spatial arrangement. The vessel is at least partially filled with a silica-containing sol, and the sol is gelled, such that a gel body with the elongate elements embedded therein is formed. Then the gel body is separated from the elongate elements (typically with the aid of a release agent), dried, purified, and sintered, and then the microstructured optical fiber is drawn from the sintered gel body. A suitable sol-gel technique is reflected, for example, in co-assigned U.S. Patent No. 5,240,488. Typically, the elongate elements are maintained in the desired spatial arrangement by holding fixtures, e.g., a bottom and a top end cap with appropriately located holes and recesses. The vessel typically is a tubular vessel, with the bottom opening of the vessel closed off by a removable cap or other appropriate closing means. The top holding fixture typically is axially movable to facilitate removal of the elongate elements from the gel body. It is also possible for the elongate elements to be physically, chemically or thermally removable, e.g., polymer rods or fibers, such that the elements are capable of being moved after gelation by, e.g., pyrolysis or chemical action.

[0017] According to this first embodiment, once the microstructured optical fiber is provided, the fiber is placed into an apparatus that heats a portion of the fiber, generally by exposure to a flame, and stretches the heated portion. For example, the taper typically reduces the diameter of the inner cladding region of initial fiber by at least a factor of 2. (The inner cladding region is the region which predominantly confines propagating modes.) A variety of apparatus suitable for such heating are known to those skilled in the art. The flame temperature is selected such that the fiber is soft enough to stretch without breaking, but not so soft that the capillary air holes collapse. As shown in Fig. 1B, the stretching results in untreated fiber regions 20, 21, two taper regions 22, 23, and a waist region 24, with the microstructure maintained through the taper regions 22, 23 and throughout the waist region 24. Maintenance of the microstructure in the waist region 24 is shown in Fig. 1C, which is a representation of waist region cross-section at *a-a'*. Fig. 1C shows the existence of capillary air holes 30, which are the stretched portions of the original capillary air holes 16 (and have a smaller diameter than the original air holes 16). The germanium-doped core 12 present in the initial fiber essentially disappears upon stretching, i.e., light in the typical communications window does not "see" a germanium-doped core when propagating through the waist region.

[0018] The capillary air holes 30 present in the taper and in the waist region confine propagating light therein, i.e., the air holes 30 provide an effective cladding layer. Thus, the core of the waist region is made up of a central silica region, with the cladding provided by an effective refractive index contrast provided by the presence of the air holes. The fiber length (i.e., treated and untreated fiber) thus provides mode contraction due to the tapering into the smaller waist region. Effects of such mode contraction are presented in Example 1 below. In addition, the taper is optionally designed to be adiabatic, i.e., where the taper does not induce coupling between modes. Thus, a fundamental mode propagating through the untreated fiber evolves into a fundamental mode in the taper and in the waist region. The ability to design an adiabatic taper is presented in Example 1 below.

[0019] Such mode contraction makes it possible, for example, to generate soliton self-frequency shifts tunable over nearly the entire communication window of interest. In particular, optical soliton pulses generally experience a continuous downshift of the carrier frequencies when propagating in a fiber with anomalous group-velocity dispersion. This soliton self-frequency shift originates from intrapulse stimulated Raman scattering, which transfers the high frequency portion of the pulse spectrum toward the low frequency portion. (See, e.g., F.M. Mitschke and L.F. Mollenauer, "Discovery of the soliton self-frequency shift," Opt. Lett., Vol. 11, 659 (1986); J.P. Gordon, "Theory of the soliton self-frequency shift," Opt. Lett., Vol. 11, 662 (1986).) While soliton self-frequency shift has attracted some attention, use of conventional fibers for generating such solitons has significant limitations. For example, due to the requirement of anomalous dispersion, the tuning range of solitons is limited by a fiber's zero dispersion wavelength. Also, conventional fibers exhibit higher-order group-velocity dispersion, which causes soliton decay or pulse breakup, and thereby severely limits the available tuning range for frequency-shifting solitons.

[0020] The invention, however, is able to provide stable, frequency-shifting solitons tunable over a relatively wide range of wavelengths, e.g., 1.3 to 1.65 μm, as reflected in Example 1. For example, the invention makes it possible to generate soliton self-frequency shifts over this range of 1.3 to 1.65 μm, with about 100 fs soliton pulses at input pulse energies of about 1 to about 3 nJ. Conversion efficiency is typically greater than 60%, optionally greater than 80%. And, as opposed to using a relatively long length, e.g., 50 m of conventional fiber, the invention is able to do so with less than 15 cm of waist region. A key to this achievement is that the process of the invention makes possible a treated fiber region that provides relatively flat (and strong) dispersion which leads to generation of a stable soliton.

[0021] In another embodiment of the invention, reflected in Fig. 2, a microstructured fiber 40 having axially

oriented elements is provided, e.g., having a germanium-doped core 42 and a cladding region containing numerous capillary air holes, e.g., 43, 44, 45 ... As shown in Fig. 2, the initial fiber is treated such that the capillary air holes, e.g., 43, 44, 45 (typically, but not necessarily all of them) are collapsed in the treated portion 46 of the fiber, optionally while the outer diameter of the treated portion 46 remains about the same as the untreated section (e.g., the outer diameter of the treated portion is at least 90% of the outer diameter of the untreated fiber). Similarly, the germanium-doped core 42 remains in the treated region. (For clarity, only the air holes 43, 44, 45 are shown in the interior of the fiber 40.) Generally, the collapse is provided by heating the treated portion to a temperature that induces collapse, but does not otherwise substantially affect the fiber. (Optionally, in this embodiment, the hole collapse is capable of being combined with some stretching or other manipulation in some or all of the treated region, to attained desired structure/properties.)

[0022] This gradual collapse as one moves along the propagation direction is able to provide mode expansion. Specifically, light propagating through the untreated portion of the fiber is guided by the germanium-doped core 42 and confined by the capillary air holes 43, 44, 45..., i.e., by the effective refractive index profile provided by the air holes. If the capillary air holes 43, 44, 45... collapse adiabatically, the mode of the propagating light continues to be guided by the germanium-doped core 42, but is now confined by a cladding or solid silica, which results in expansion of the mode of the propagating light.

[0023] A variety of suitable fiber microstructures, including a variety of configurations for the axially oriented elements, are possible, and are known in the art. Capillary air holes, of a variety of shapes and configurations, are generally useful. Axially oriented elements containing other materials are also possible. Selection of an appropriate microstructure is within the ability of one skilled in the art, following the guidelines herein.

[0024] An example of such an additional fiber is microstructured fiber in which the axially oriented elements are arranged periodically, to provide a bandgap effect. Such fibers are known in the art as photonic bandgap fibers or photonic crystal fiber. (See, e.g., J.C. Knight et al., "Photonic bandgap guidance in optical fiber," Science, Vol. 282, 1476 (1998).) It would be possible according to the invention, for example, to provide a taper in such a periodically structured fiber, such that the taper would adjust the spacing of the axially oriented elements and thereby change the bandgap frequency of the fiber. Other modifications of such periodically structured fiber are also possible.

[0025] Another possible microstructured fiber capable of being treated according to the invention contain dopants, e.g., rare earths, in a portion or the entirety of the fiber length, to provide active devices. For example, it is possible to dope a treated region. e.g., with a rare earth such as Yb or Pr, to provide fiber lasers at desired wavelengths. Doping to enhance optical nonlinearity is also possible. Such nonlinearities are also possible by use of fiber formed from nonlinear material, such as chalcogenide and other non-silica materials. Other uses of doped or non-silica fibers according to the invention will be apparent to one skilled in the art.

[0026] A variety of modifications and combinations involving heating and stretching a microstructured fiber are also possible. For example, it is possible to have only one taper region, and/or to have the air holes collapse somewhere in the taper region or regions, or somewhere in the waist region. One possible combination of tapering and collapse increases the ease with which a microstructured fiber is coupled to standard single mode fiber. For example, it is possible to take a microstructured (with capillary air holes) fiber having an outer diameter of about 200 μm, stretch one end down to a smaller diameter to provide desired non-linearities, and heat the opposite end to collapse the air holes (with some accompanying reduction in the outer diameter). The end with the collapsed holes thereby becomes solid material, which is much easier to splice and to couple to standard transmission fiber. And the stretched end is capable of providing the unique properties discussed herein. Other combinations of techniques are also possible. It is also possible to treat a fiber during draw, and the term treating, as used herein, is intended to include adjustments to, e.g., heating and/or tension, during draw.

[0027] The invention will be further clarified by the following example, which is intended to be exemplary.

Example 1

[0028] A microstructured fiber was obtained, having a 8 μm germanium-doped silica core, a inner cladding region diameter of about 40 μm, an outer diameter of 132 μm. and a ring of six capillary air holes located circumferentially in the cladding region. Fig. 3B is a representation of the size and configuration of the initial fiber. The fiber was formed by taking an initial preform containing a germanium core, bundling six tubes around the initial preform, overcladding the bundle with a silica tube, consolidating the resultant assembly into a preform, and drawing fiber from the preform. The fiber was placed into a fiber stretching apparatus, heated with a flame to about 1400-1500°C (near its melting point) and stretched. The fiber was stretched to provide a waist region having a central silica region of about 2.5 μm (with the germanium core essentially disappearing due to the stretching) surrounded by the air holes, an outer diameter of 10 μm, and a length of about 10 to 20 cm, with two tapers at either end of the waist, the tapers having a length of about 0.60 cm. (The overall fiber length resembled the length shown in Fig. 1B.) The microstructure of the initial fiber was maintained in the tapers and throughout the waist region, i.e., the capillary air holes

did not collapse. Fig. 3A is a representation of the size and configuration of the fiber in the waist region.

[0029] The adiabatic nature of the taper was examined using the Beam Propagation method (see B. J. Eggleton et al., "Cladding-mode-resonances in air-silica microstructure optical fibers," Journal of Lightwave Technology, Vol. 18, 1084-1100 (2000)), which examines a launch through a fiber by solving Maxwell's equations at small steps along the propagation direction. For the 132 μm outer diameter fiber tapered down to a 10 μm outer diameter fiber over a length of 0.60 cm, the adiabacity of the taper was confirmed.

[0030] In addition, the effect of decreasing the mode size from the initial microstructured fiber down to the waist region fiber was examined, using BPM. Fig. 4A shows the dispersion as a function of the diameter of the taper, and Fig. 4B shows the intensity as a function of the diameter of the taper. The dispersion is initially similar to that of standard fiber, but as the mode becomes confined within the air holes, the waveguide dispersion becomes more significant. As for intensity, because the taper has relatively low loss, the decrease in mode diameter (from 10 μm to < 3μm) is accompanied by an approximately 16-fold increase in intensity.

[0031] The fact that the light propagating in this taper was confined within the capillary air holes was confirmed by surrounding the taper (and waist) with an index matching fluid, and measuring any power loss in the system. The power loss from the taper and waist was less than 0.15 dB.

[0032] Nonlinear effects of the fiber length were examined. 1.3 μm laser pulses generated by a femtosecond Ti-sapphire pumped optical parametric oscillator were free-space coupled into the untreated portion of the fiber and propagated through the taper into the waist. The output spectra from the waist, measured at different incident peak powers, is shown in Fig. 5. As can be seen, tunable self-frequency shifting solitons were generated over the communications windows from 1.3 μm to 1.65 μm. In particular, as the light propagated through the length of fiber, the light was continually shifted towards the red due to intrapulse Raman scattering, which transfers the energy of the high frequency part of the pulse spectrum to the low frequency part. It was observed that 80 to 90% of the input power was self-frequency shifted.

[0033] Because the treated fiber length exhibited a widely-flattened dispersion curve, it is apparent that the soliton wavelength is capable of being tuned over a wide spectral range by adjusting the input power, and is also stable against instability at high peak intensities. Moreover, soliton-effect pulse compression was exhibited by the treated fiber length - 400 fs pulses at 1.55 um were efficiently compressed by a factor of 5 to 80 fs, as reflected in Fig. 5.

[0034] Other embodiments of the invention will be apparent to those skilled in the art from consideration of the specification and practice of the invention disclosed herein.

Claims

1. A process for forming a tapered optical fiber article, having the steps of:

   providing a microstructured optical fiber that comprises a core region of doped glass (12), a cladding region (14) of glass peripherally surrounding the core comprising a microstructure of one or more axially oriented elements consisting of capillary air holes (16) located in the cladding region; and
   treating a portion of the fiber by heating and optionally stretching,

   wherein the treatment is performed such that light propagating through the treated portion of the fiber is confined by the capillary air holes or by the treated cladding region, and at least one feature of the microstructure of the fiber is modified along the propagation direction, and light propagating through the untreated portion of the fiber is guided by the doped core region and the axially oriented elements play substantially no role in waveguiding in the untreated regions.

2. The process of claim 1, wherein the at least one feature is selected from the group consisting of fiber outer diameter and cross-section of the axially oriented elements.

3. The process of claim 1, wherein the axially oriented elements are capillary air holes.

4. The process of claim 3, wherein the capillary air holes are located circumferentially around the core region.

5. The process of claim 1, wherein the treatment step comprises stretching.

6. The process of claim 5, wherein the stretching provides the treated portion with at least one tapered region and a waist region, the at least one tapered region leading from an untreated portion of the fiber to the waist region.

7. The process of claim 6, wherein the microstructure of the fiber is maintained in the at least one tapered region, and wherein the microstructure of the fiber and of the at least one tapered region is maintained in at least a portion of the waist region.

8. The process of claim 7, wherein light propagating through the fiber in at least part of the at least one

tapered region and in the waist region is confined by the one or more axially oriented elements.

9. The process of claim 7, wherein the at least one tapered region is adiabatically tapered, such that a fundamental mode propagating through the unstretched fiber will evolve into a fundamental mode inside the waist region.

10. The process of claim 7, wherein the microstructure of the fiber is maintained throughout the waist region.

11. The process of claim 6, wherein the tapered region provides a decrease in diameter of an inner cladding region from the untreated fiber to the waist region of at least a factor of 2.

12. The process of claim 1, wherein the axially oriented elements are periodically spaced in the cladding region.

13. The process of claim 12, wherein the periodically spaced axially oriented elements provide a photonic bandgap effect.

14. The process of claim 3, wherein the treating step partially or fully collapses one or more of the capillary air holes in at least a part of the treated portion.

15. The process of claim 14, wherein the treating step fully collapses one or more of the capillary air holes in at least a part of the treated portion.

16. The process of claim 14, wherein all the capillary air holes are partially or fully collapsed in at least a part of the treated portion.

17. The process of claim 14, wherein the collapse is induced by heat in the absence of stretching.

18. The process of claim 14, wherein the outer diameter of the treated fiber is at least 90% of the outer diameter of the untreated fiber.

19. The process of claim 14, wherein light propagating from the untreated portion of the fiber to the treated portion experiences mode expansion.

20. The process of claim 6, wherein the provided microstructured fiber comprises a germanium-doped core.

21. The process of claim 14, wherein the provided microstructured fiber comprises a germanium-doped core.

22. The process of claim 1, wherein the treated portion of the fiber comprises one or more dopants.

23. The process of claim 1 wherein the fiber comprises one or more materials that induce or enhance optical nonlinearity in the fiber length.

24. A system comprising a tapered optical fiber article having:

a length of microstructured optical fiber that comprises a core region of doped glass (12), a cladding region (14) of glass peripherally surrounding the core comprising a microstructure of one or more axially oriented elements (16) consisting of capillary air holes (16) located in the cladding region, the length of microstructured fiber comprising at least one untreated portion (20) adjacent to one or more treated portions (24); and

the treated portion, treated such that light propagating through the treated portion of the fiber is confined by the capillary air holes or by the treated cladding region, and comprising at least one tapered region (22) that leads from the untreated portion of the microstructured optical fiber into a waist region (24), wherein the microstructure of the fiber is maintained in at least part of the at least one tapered region (22); and

a collapsed region in which at least some of the one or more axially oriented elements are partially or fully collapsed, and light propagating through the untreated portion of the fiber is guided by the doped core region and the axially oriented elements play substantially no role in waveguiding in the untreated regions.

25. The system of claim 24, wherein at least one of the treated portions comprises the at least one tapered region, and wherein the at least one tapered region is adiabatically tapered, such that a fundamental mode propagating through the microstructured optical fiber outside the waist region will evolve into a fundamental mode in the fiber inside the waist region.

26. The system of claim 24, wherein the microstructure of the fiber is maintained throughout the tapered region, and wherein the microstructure of the fiber and of the tapered region is maintained in at least a portion of the waist region.

27. The system of claim 26, wherein light propagating through the fiber in the at least one tapered region and inside the waist region is confined by the one or more axially oriented elements.

28. The system of claim 26, wherein the microstructure of the fiber is maintained throughout the waist region.

29. The system of claim 24, wherein at least one of the treated portions comprises the at least one tapered region, and wherein the at least one tapered region provides a decrease in diameter of an inner cladding region from the untreated fiber to the waist region of at least a factor of 2.

30. The system of claim 24, wherein at least one of the treated portions comprises the at least one tapered region, and wherein light propagating from the untreated fiber through one of the at least one tapered regions and into the waist region experiences mode contraction.

31. The system of claim 24, wherein at least one of the treated portions comprises the collapsed region, and wherein all the axially oriented elements are partially or full collapsed in at least a part of the treated portion.

32. The system of claim 24, wherein at least one of the treated portions comprises the collapsed region, and wherein at least some of the axially oriented elements are fully collapsed in at least a part of the treated portion.

33. The system of claim 24, wherein at least one of the treated portions comprises the collapsed region, and wherein the outer diameter of the treated portion of the fiber is at least 90% of the outer diameter of the untreated portion of the fiber.

34. The system of claim 24, wherein at least one of the treated portions comprises the collapsed region, and wherein light propagating from the untreated portion of the fiber to the treated portion experiences mode expansion.

35. The system of claim 24, wherein the microstructured fiber comprises a germanium-doped core.

36. The system of claim 24, wherein the axially oriented elements are periodically spaced in the cladding region.

37. The system of claim 36, wherein the periodically spaced axially oriented elements provide a photonic bandgap effect.

38. The system of claim 24, wherein the treated portion of the fiber comprises one or more dopants.

39. The system of claim 24, wherein the fiber comprises one or more materials that induce or enhance optical nonlinearity in the system.

Patentansprüche

1. Verfahren zur Herstellung eines sich verjüngenden faseroptischen Artikels, mit folgenden Schritten:

   Bereitstellen einer mikrostrukturierten optischen Faser, umfassend eine Kernregion aus dotiertem Glas (12) und eine Ummantelungsregion (14) aus Glas, das den Kern peripher umgibt und eine Mikrostruktur aus einem oder mehreren axial ausgerichteten Elementen, die aus kapillarischen Luftlöchern (16) bestehen und sich in der Ummantelungsregion befinden, umfasst und
   Behandeln eines Abschnitts der Faser mittels Erwärmen und optionalem Strecken,

   wobei die Behandlung dergestalt erfolgt, dass Licht, das sich durch den behandelten Abschnitt der Faser hindurch ausbreitet, durch die kapillarischen Luftlöcher oder durch die behandelte Ummantelungsregion eingegrenzt wird, und wobei wenigstens ein Merkmal der Mikrostruktur der Faser entlang der Ausbreitungsrichtung modifiziert ist, und wobei Licht, das sich durch den unbehandelten Abschnitt der Faser hindurch ausbreitet, mittels der dotierten Kernregion geleitet wird und die axial ausgerichteten Elemente im Wesentlichen keine Rolle für das Wellenleiten in den unbehandelten Regionen spielen.

2. Verfahren nach Anspruch 1, wobei es sich bei dem wenigstens einen Merkmal entweder um den Außendurchmesser der Faser oder um den Querschnitt der axial ausgerichteten Elemente handelt.

3. Verfahren nach Anspruch 1, wobei es sich bei den axial ausgerichteten Elementen um kapillarische Luftlöcher handelt.

4. Verfahren nach Anspruch 3, wobei die kapillarischen Luftlöcher umfangsmäßig um die Kernregion herum angeordnet sind.

5. Verfahren nach Anspruch 1, wobei der Behandlungsschritt Strecken umfasst.

6. Verfahren nach Anspruch 5, wobei das Strecken in dem behandelten Abschnitt die Herausbildung wenigstens einer sich verjüngenden Region und einer taillierten Region zum Ergebnis hat, wobei die wenigstens eine sich verjüngende Region von einem unbehandelten Abschnitt der Faser zur taillierten Region führt.

7. Verfahren nach Anspruch 6, wobei die Mikrostruktur der Faser in der wenigstens einen sich verjüngenden Region beibehalten bleibt und wobei die Mi-

krostruktur der Faser und der wenigstens einen sich verjüngenden Region in wenigstens einem Abschnitt der taillierten Region beibehalten bleibt.

8. Verfahren nach Anspruch 7, wobei Licht, das sich durch die Faser in wenigstens einem Teil der wenigstens einen sich verjüngenden Region und in der taillierten Region hindurch ausbreitet, durch das eine oder die mehreren axial ausgerichteten Elemente eingegrenzt wird.

9. Verfahren nach Anspruch 7, wobei die wenigstens eine sich verjüngende Region sich adiabatisch verjüngt, dergestalt, dass eine Grundwelle, die sich durch die nicht gestreckte Faser hindurch ausbreitet, sich zu einer Grundwelle im Inneren der taillierten Region entwickelt.

10. Verfahren nach Anspruch 7, wobei die Mikrostruktur der Faser durch die gesamte taillierte Region hindurch beibehalten bleibt.

11. Verfahren nach Anspruch 6, wobei die sich verjüngende Region eine mindestens z-fache Verringerung des Durchmessers einer inneren Ummantelungsregion von der unbehandelten Faser zu der taillierten Region aufweist.

12. Verfahren nach Anspruch 1, wobei die axial ausgerichteten Elemente in der Ummantelungsregion periodisch voneinander beabstandet sind.

13. Verfahren nach Anspruch 12, wobei die periodisch voneinander beabstandeten axial ausgerichteten Elemente einen photonischen Bandlückeneffekt bewirken.

14. Verfahren nach Anspruch 3, wobei der Behandlungsschritt zu einem teilweisen oder vollständigen Zusammenfallen eines oder mehrerer der kapillarischen Luftlöcher in wenigstens einem Teil des behandelten Abschnitts führt.

15. Verfahren nach Anspruch 14, wobei der Behandlungsschritt zu einem vollständigen Zusammenfallen eines oder mehrerer der kapillarischen Luftlöcher in wenigstens einem Teil des behandelten Abschnitts führt.

16. Verfahren nach Anspruch 14, wobei alle kapillarischen Luftlöcher in wenigstens einem Teil des behandelten Abschnitts teilweise oder vollständig zum Zusammenfallen gebracht werden.

17. Verfahren nach Anspruch 14, wobei das Zusammenfallen durch Wärme und ohne Strecken hervorgerufen wird.

18. Verfahren nach Anspruch 14, wobei der Außendurchmesser der behandelten Faser wenigstens 90% des Außendurchmessers der unbehandelten Faser misst.

19. Verfahren nach Anspruch 14, wobei Licht, das sich von dem unbehandelten Abschnitt der Faser zu dem behandelten Abschnitt ausbreitet, einer Wellentypausweitung unterliegt.

20. Verfahren nach Anspruch 6, wobei die resultierende mikrostrukturierte Faser einen germaniumdotierten Kern umfasst.

21. Verfahren nach Anspruch 14, wobei die resultierende mikrostrukturierte Faser einen germaniumdotierten Kern umfasst.

22. Verfahren nach Anspruch 1, wobei der behandelte Abschnitt der Faser eine oder mehrere Dotierungssubstanzen umfasst.

23. Verfahren nach Anspruch 1, wobei die Faser ein oder mehrere Materialien umfasst, welche optische Nichtlinearität in der Faserlänge induzieren oder verbessern.

24. System, umfassend einen sich verjüngenden faseroptischen Artikel mit:

einem Streckenabschnitt aus einer mikrostrukturierten optischen Faser, umfassend eine Kernregion aus dotiertem Glas (12) und eine Ummantelungsregion (14) aus Glas, welche den Kern peripher umgibt und eine Mikrostruktur aus einem oder mehreren axial ausgerichteten Elementen (16), die aus kapillarischen Luftlöchern (16) bestehen und sich in der Ummantelungsregion befinden, umfasst, wobei der Streckenabschnitt aus einer mikrostrukturierten optischen Faser neben einem oder mehreren behandelten Abschnitten (24) wenigstens einen unbehandelten Abschnitt (20) umfasst; und

dem behandelten Abschnitt, der so behandelt ist, dass Licht, das sich durch den behandelten Abschnitt der Faser hindurch ausbreitet, durch die kapillarischen Luftlöcher oder durch die behandelte Ummantelungsregion eingegrenzt wird, und der wenigstens eine sich verjüngende Region (22) umfasst, die von dem unbehandelten Abschnitt der mikrostrukturierten optischen Faser in eine taillierte Region (24) hineinführt, in welcher die Mikrostruktur der Faser in wenigstens einem Teil der wenigstens einen sich verjüngenden Region (22) beibehalten bleibt; und einer zusammengefallenen Region, in der wenigstens einige des einen oder der mehreren

axial orientierten Elemente teilweise oder vollständig zusammengefallen sind, und wobei Licht, das sich durch den unbehandelten Abschnitt der Faser hindurch ausbreitet, mittels der dotierten Kernregion geleitet wird, und wobei die axial ausgerichteten Elemente im Wesentlichen keine Rolle für das Wellenleiten in den unbehandelten Regionen spielen.

25. System nach Anspruch 24, wobei wenigstens einer der behandelten Abschnitte die wenigstens eine sich verjüngende Region umfasst und wobei die wenigstens eine sich verjüngende Region sich adiabatisch verjüngt, dergestalt, dass eine Grundwelle, die sich durch die mikrostrukturierte optische Faser außerhalb der taillierten Region hindurch ausbreitet, sich zu einer Grundwelle in der Faser im Inneren der taillierten Region entwickelt.

26. System nach Anspruch 24, wobei die Mikrostruktur der Faser in der gesamten sich verjüngenden Region beibehalten bleibt und wobei die Mikrostruktur der Faser und der sich verjüngenden Region in wenigstens einem Abschnitt der taillierten Region beibehalten bleibt.

27. System nach Anspruch 26, wobei Licht, das sich durch die Faser in der wenigstens einen sich verjüngenden Region und im Inneren der taillierten Region hindurch ausbreitet, durch das eine oder die mehreren axial ausgerichteten Elemente eingegrenzt wird.

28. System nach Anspruch 26, wobei die Mikrostruktur der Faser durch die gesamte taillierte Region hindurch beibehalten bleibt.

29. System nach Anspruch 24, wobei wenigstens einer der behandelten Abschnitte die wenigstens eine sich verjüngende Region umfasst und wobei die wenigstens eine sich verjüngende Region eine mindestens 2-fache Verringerung des Durchmessers einer inneren Ummantelungsregion von der unbehandelten Faser zu der taillierten Region aufweist.

30. System nach Anspruch 24, wobei wenigstens einer der behandelten Abschnitte die wenigstens eine sich verjüngende Region umfasst und wobei Licht, das sich von der unbehandelten Faser durch eine der wenigstens einen sich verjüngenden Region und in die taillierte Region hinein ausbreitet, einer Wellentypkontraktion unterliegt.

31. System nach Anspruch 24, wobei wenigstens einer der behandelten Abschnitte die zusammengefallene Region umfasst und wobei alle axial orientierten Elemente in wenigstens einem Teil des behandelten Abschnitts teilweise oder vollständig zusammengefallen sind.

32. System nach Anspruch 24, wobei wenigstens einer der behandelten Abschnitte die zusammengefallene Region umfasst und wobei wenigstens einige der axial orientierten Elemente in wenigstens einem Teil des behandelten Abschnitts vollständig zusammengefallen sind.

33. System nach Anspruch 24, wobei wenigstens einer der behandelten Abschnitte die zusammengefallene Region umfasst und wobei der Außendurchmesser des behandelten Abschnitts der Faser wenigstens 90% des Außendurchmessers des unbehandelten Abschnitts der Faser misst.

34. System nach Anspruch 24, wobei wenigstens einer der behandelten Abschnitte die zusammengefallene Region umfasst und wobei Licht, das sich von dem unbehandelten Abschnitt der Faser zu dem behandelten Abschnitt ausbreitet, einer Wellentypausweitung unterliegt.

35. System nach Anspruch 24, wobei die mikrostrukturierte Faser einen germaniumdotierten Kern umfasst.

36. System nach Anspruch 24, wobei die axial ausgerichteten Elemente in der Ummantelungsregion periodisch voneinander beabstandet sind.

37. System nach Anspruch 36, wobei die periodisch voneinander beabstandeten axial ausgerichteten Elemente einen photonischen Bandlückeneffekt bewirken.

38. System nach Anspruch 24, wobei der behandelte Abschnitt der Faser eine oder mehrere Dotierungssubstanzen umfasst.

39. System nach Anspruch 24, wobei die Faser ein oder mehrere Materialien umfasst, welche optische Nichtlinearität in dem System induzieren oder verbessern.

Revendications

1. Procédé de formage d'un article à fibre optique conique, comportant les étapes qui consistent à :

fournir une fibre optique microstructurée qui comprend une zone centrale de verre dopé (12), une zone formée d'une gaine (14) de verre entourant périphériquement la zone centrale et comprenant une microstructure formée d'un ou plusieurs éléments orientés axialement constitués de trous d'air capillaires (16) situés dans

la zone formée d'une gaine ; et
traiter une partie de la fibre par chauffage et éventuellement par étirage,

dans lequel le traitement a lieu de sorte que la lumière se propageant à travers la partie traitée de la fibre soit limitée par les trous d'air capillaires ou par la zone formée d'une gaine traitée, et qu'au moins une caractéristique de la microstructure de la fibre soit modifiée le long de la direction de propagation, que la propagation de la lumière à travers la partie non traitée de la fibre soit guidée par la zone centrale dopée, et que les éléments orientés axialement ne jouent fondamentalement aucun rôle dans le guidage des ondes dans les zones non traitées.

2. Procédé selon la revendication 1, dans lequel ladite caractéristique au moins est sélectionnée dans le groupe constitué du diamètre extérieur de la fibre et de la section transversale des éléments orientés axialement.

3. Procédé selon la revendication 1, dans lequel les éléments orientés axialement sont des trous d'air capillaires.

4. Procédé selon la revendication 3, dans lequel les trous d'air capillaires sont situés circonférentiellement autour de la zone centrale.

5. Procédé selon la revendication 1, dans lequel l'étape de traitement comprend l'étirage.

6. Procédé selon la revendication 5, dans lequel l'étirage produit au moins une zone conique et un étranglement dans la partie traitée, ladite zone conique au moins s'étendant à partir d'une partie non traitée de la fibre jusqu'à l'étranglement.

7. Procédé selon la revendication 6, dans lequel la microstructure de la fibre est maintenue dans ladite zone conique au moins, et dans lequel la microstructure de la fibre et de ladite zone conique au moins est maintenue dans au moins une partie de l'étranglement.

8. Procédé selon la revendication 7, dans lequel la lumière se propageant à travers la fibre dans au moins une partie de ladite zone conique au moins et dans l'étranglement est limitée par ledit ou lesdits élément(s) orienté(s) axialement.

9. Procédé selon la revendication 7, dans lequel ladite zone conique au moins a une conicité adiabatique, de sorte qu'un mode fondamental se propageant à travers la fibre non étirée produise un mode fondamental à l'intérieur de l'étranglement.

10. Procédé selon la revendication 7, dans lequel la microstructure de la fibre est maintenue à travers l'étranglement.

11. Procédé selon la revendication 6, dans lequel la zone conique produit une diminution du diamètre d'une zone formée d'une gaine interne à partir de la fibre non traitée jusqu'à l'étranglement, en divisant le diamètre par 2 au moins.

12. Procédé selon la revendication 1, dans lequel les éléments orientés axialement sont espacés périodiquement dans la zone formée d'une gaine.

13. Procédé selon la revendication 12, dans lequel les éléments orientés axialement et espacés périodiquement produisent un effet de bande interdite photonique.

14. Procédé selon la revendication 3, dans lequel l'étape de traitement entraîne un effondrement partiel ou total d'un ou plusieurs des trous d'air capillaires dans au moins une partie de la partie traitée.

15. Procédé selon la revendication 14, dans lequel l'étape de traitement entraîne un effondrement total d'un ou plusieurs des trous d'air capillaires dans au moins une partie de la partie traitée.

16. Procédé selon la revendication 14, dans lequel tous les trous d'air capillaires sont partiellement ou totalement effondrés dans au moins une partie de la partie traitée.

17. Procédé selon la revendication 14, dans lequel l'effondrement est induit par la chaleur en l'absence d'étirage.

18. Procédé selon la revendication 14, dans lequel le diamètre extérieur de la fibre traitée correspond à 90 % au moins du diamètre extérieur de la fibre non traitée.

19. Procédé selon la revendication 14, dans lequel la lumière se propageant à partir de la partie non traitée de la fibre jusqu'à la partie traitée subit une expansion de mode.

20. Procédé selon la revendication 6, dans lequel la fibre microstructurée fournie comprend une zone centrale dopée au germanium.

21. Procédé selon la revendication 14, dans lequel la fibre microstructurée fournie comprend une zone centrale dopée au germanium.

22. Procédé selon la revendication 1, dans lequel la partie traitée de la fibre comprend un ou plusieurs

dopants.

23. Procédé selon la revendication 1, dans lequel la fibre comprend un ou plusieurs matériaux qui induisent ou augmentent la non-linéarité optique dans la longueur de la fibre.

24. Système comprenant un article à fibre optique conique comportant :

une longueur de fibre optique microstructurée qui comprend une zone centrale de verre dopé (12), une zone formée d'une gaine (14) de verre entourant périphériquement la zone centrale et comprenant une microstructure formée d'un ou plusieurs éléments orientés axialement constitués de trous d'air capillaires (16) situés dans la zone formée d'une gaine, la longueur de la fibre microstructurée comprenant au moins une partie non traitée (20) adjacente à une ou plusieurs parties traitées (24) ; et
la partie traitée, traitée de sorte que la lumière se propageant à travers la partie traitée de la fibre soit limitée par les trous d'air capillaires ou par la zone formée d'une gaine traitée, et comprenant au moins une zone conique (22) qui s'étend à partir de la partie non traitée de la fibre optique microstructurée jusqu'à un étranglement (24), dans lequel la microstructure de la fibre est maintenue dans au moins une partie de ladite zone conique au moins (22) ; et
une zone effondrée dans laquelle certains au moins dudit ou desdits élément(s) orienté(s) axialement sont partiellement ou totalement effondrés, la lumière se propageant à travers la partie non traitée de la fibre est guidée par la zone centrale dopée, et les éléments orientés axialement ne jouent fondamentalement aucun rôle dans le guidage des ondes dans les zones non traitées.

25. Système selon la revendication 24, dans lequel l'une au moins des parties traitées comprend ladite zone conique au moins, et dans lequel ladite zone conique au moins a une conicité adiabatique, de sorte qu'un mode fondamental se propageant à travers la fibre optique microstructurée en dehors de l'étranglement produise un mode fondamental dans la fibre à l'intérieur de l'étranglement.

26. Système selon la revendication 24, dans lequel la microstructure de la fibre est maintenue à travers la zone conique, et dans lequel la microstructure de la fibre et de la zone conique est maintenue dans au moins une partie de l'étranglement.

27. Système selon la revendication 26, dans lequel la lumière se propageant à travers la fibre dans ladite zone conique au moins et à l'intérieur de l'étranglement est limitée par ledit ou lesdits élément(s) orienté(s) axialement.

28. Système selon la revendication 26, dans lequel la microstructure de la fibre est maintenue à travers l'étranglement

29. Système selon la revendication 24, dans lequel l'une au moins des parties traitées comprend ladite zone conique au moins, et dans lequel ladite zone conique au moins produit une diminution du diamètre d'une zone formée d'une gaine interne à partir de la fibre non traitée jusqu'à l'étranglement, en divisant le diamètre par 2 au moins.

30. Système selon la revendication 24, dans lequel l'une au moins des parties traitées comprend ladite zone conique au moins, et dans lequel la lumière se propageant à partir de la fibre non traitée, à travers une zone conique parmi lesdites zones coniques au moins et dans l'étranglement, subit une contraction de mode.

31. Système selon la revendication 24, dans lequel l'une au moins des parties traitées comprend la région effondrée, et dans lequel tous les éléments orientés axialement sont partiellement ou totalement effondrés dans au moins une partie de la partie traitée.

32. Système selon la revendication 24, dans lequel l'une au moins des parties traitées comprend la région effondrée, et dans lequel certains au moins des éléments orientés axialement sont totalement effondrés dans au moins une partie de la partie traitée.

33. Système selon la revendication 24, dans lequel l'une au moins des parties traitées comprend la région effondrée, et dans lequel le diamètre extérieur de la partie traitée de la fibre correspond à 90 % au moins du diamètre extérieur de la partie non traitée de la fibre.

34. Système selon la revendication 24, dans lequel l'une au moins des parties traitées comprend la région effondrée, et dans lequel la lumière se propageant à partir de la partie non traitée de la fibre jusqu'à la partie traitée subit une expansion de mode.

35. Système selon la revendication 24, dans lequel la fibre microstructurée comprend une zone centrale dopée au germanium.

36. Système selon la revendication 24, dans lequel les éléments orientés axialement sont espacés périodiquement dans la zone formée d'une gaine.

37. Système selon la revendication 36, dans lequel les éléments orientés axialement et espacés périodiquement produisent un effet de bande interdite photonique.

38. Système selon la revendication 24, dans lequel la partie traitée de la fibre comprend un ou plusieurs dopants.

39. Système selon la revendication 24, dans lequel la fibre comprend un ou plusieurs matériaux qui induisent ou augmentent la non-linéarité optique dans le système.

FIG. 1a

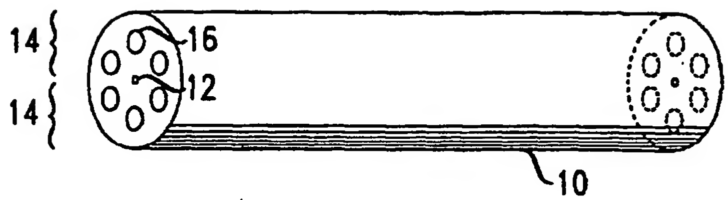

FIG. 1b

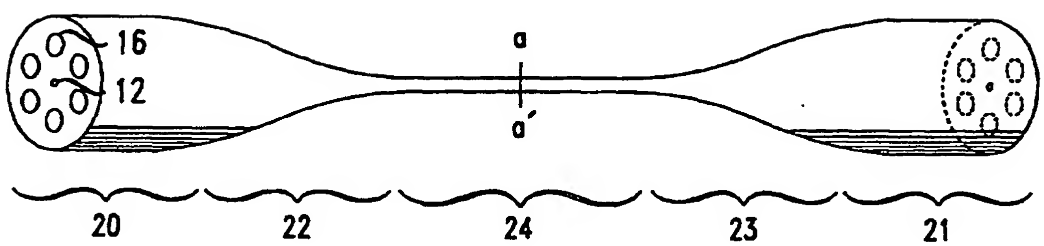

FIG. 1c

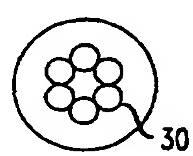

FIG. 2

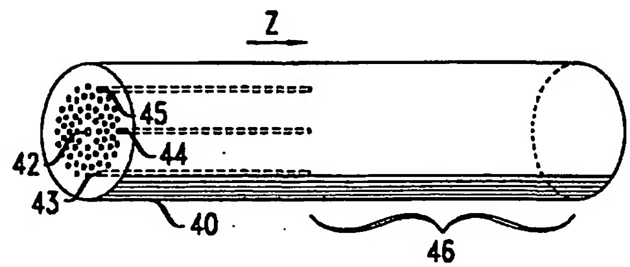

FIG. 3a

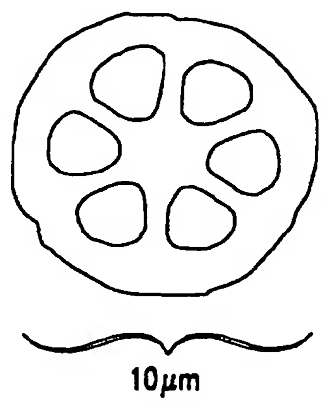

FIG. 3b

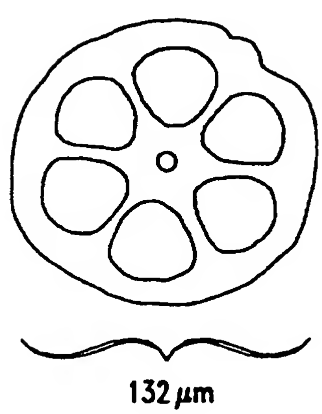

FIG. 4a

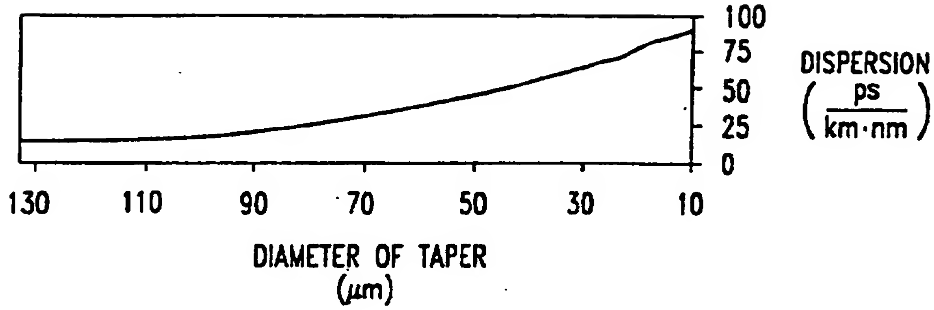

FIG. 4b

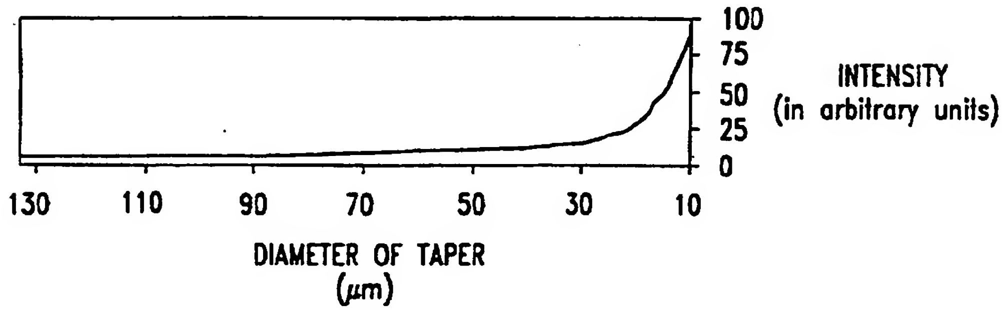

FIG. 5